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Railway track subgrade failure mechanisms using a fault chart approach

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Abstract

Railway track subgrade failure induced by climate related softening, may lead to unplanned maintenance costs and consequential and costly train delays. The softening process can be due to the presence of water in the upper parts of the track foundation due to inadequate drainage system or poorly maintained railway track drainage. In order to better make use of scarce resources and plan railway track and associated drainage maintenance rationally it would be helpful to better understand and quantify the relationships between the causes of poor subgrade and the railway track drainage system. The understanding of railway track drainage associated failure can be further used to infer engineering knowledge into railway performance models and associated risk analysis methodologies. To this end, this paper describes the development of a fault tree analysis approach which considers the failure mode(s) for railway track subgrade. The fault chart has been developed in two stages, in the first stage, failure mechanisms are diagnosed utilizing a cause-effect diagram, and in the second stage a fault tree analysis (FTA) is performed.

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Keywords: soft subgrade; track drainage; maintenance; risk analysis; failure mode(s); fault chart; cause-effect diagram; fault tree analysis (FTA).

1. Introduction

Conventional ballasted railway track (Fig. 1) is a structural system designed to withstand the combined damaging effects of the traffic and the environment for a predetermined period of time, so that train operating costs and passenger comfort and safety are within acceptable limits and the subgrade soil is adequately protected [1–4]

The integrity of the track support system relies to a large extent on the adequate removal of water via the ballast

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and appropriate designed surface and sub-surface drainage [1]. This particularly so where railway track is founded on fine grained subgrade soils (such as clays and slits), since the load bearing properties of such soils is particularly sensitive to moisture [5].

Excessive amounts of water in the upper part of railway track foundation can be led to softening and in consequence a variety of types of track failure [1]. This in turn can lead to unplanned railway track maintenance and the costly imposition of train speed restrictions [6]. It is therefore important for railway track asset managers to ensure that adequate drainage is provided at the design stage and that existing drainage systems are inspected at appropriate intervals. Much existing railway track however is aged [7] and the capacity of its drainage infrastructure is unknown. These pose problems for the track drainage asset manager in the use of scarce resources for inspecting track drainage, identifying likely drainage issues and planning remedial action.

To facilitate railway drainage asset management this paper proposes and describes the development of a fault chart as a systematic means of identifying the possible causes and risks of the railway track subgrade failure associated with inadequate drainage. First using Cause and Effect Analysis, railway track subgrade failure process are described and linked in logical sequence. Thereafter, a fault tree analysis is established for risk identification based on the potential threat of hazard events.

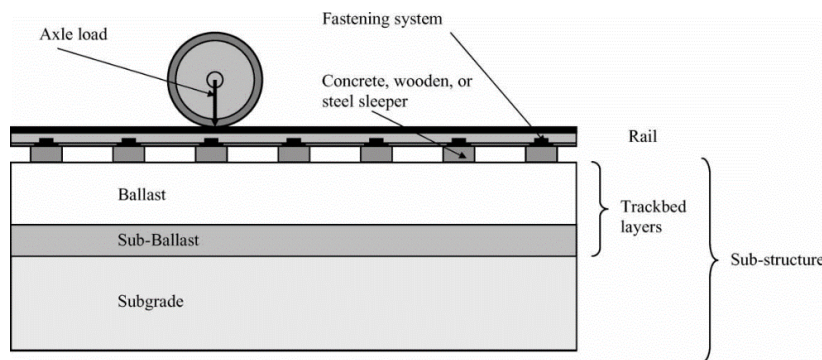


Fig. 1. Ballasted rail track typical section (source: [4]).

2. Failure type affected by inadequate railway track drainage

Failure modes of fine subgrade soils, exacerbated by the presence of water are described as follows:

2.1. Subgrade progressive shear failure

Progressive shear failure develops at the subgrade surface as the soil is sheared and remoulded due to cyclic over-stressing. In this type of failure the surface of the subgrade gradually squeezes outward and upward following the path of least resistance (Fig. 2) [4,8].

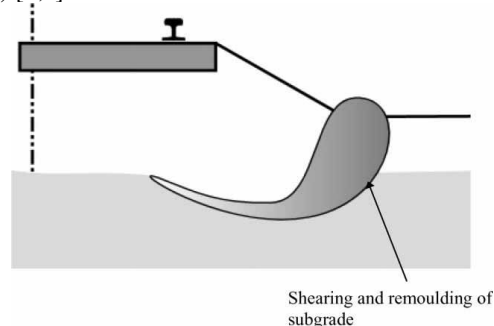


Fig. 2. Subgrade progressive shear failure (source: [4] after [8]).

2.2. Excessive Subgrade Plastic Deformation

The problem of an excessive rate of settlement through plastic deformation usually results in a ballast pocket forming as shown in Fig. 3 [4,8]. The ballast pocket is formed from the vertical component of shear deformation caused by progressive compaction of the subgrade layer resulting from repeated loading [8].

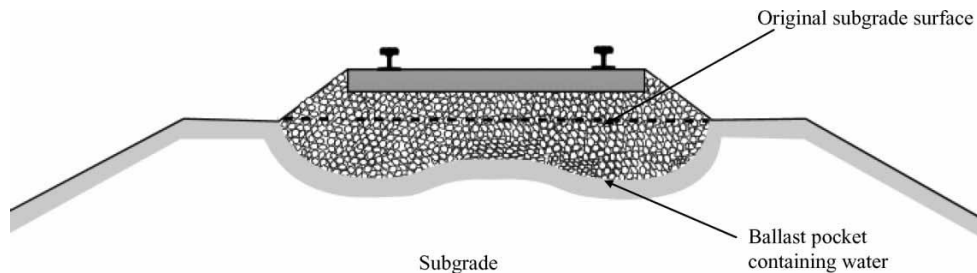


Fig. 3. Excessive subgrade plastic deformation (source : [4] after [8]).

2.3. Attrition with mud pumping

The migration of fines, or mud pumping, causes the ballast to become contaminated and thus lessens its ability to carry load and eventually results in the loss of track geometry and the formation of wet spots. The consequential loss of track geometry may lead to worsening ride quality, the possible imposition of speed restrictions and an increase in maintenance cost. In the UK the problem is widespread, for example, Ghataora et al. [9], found that there are on average 5 wet spots per mile of track (Fig. 4). The problem is little understood, although it has been attributed to aggregates pushing down on the subgrade surface, causing local stress concentrations and therefore subgrade softening and that under dynamic loading, particularly in the presence of water the continual reworking of the softened soil may result in slurry being formed. The formation of slurry has also been attributed to the attrition of the subgrade by the ballast, under dynamic train loads in the presence of water [9,10].



Fig. 4. Wet spots (source: [11]).

In addition to the main types of track subgrade failure described above, a number of less common types of failure include [11]:

- Liquefaction: a large displacement caused by repeated loading, saturated silt, and fine sand.
- Massive shear failure (slope stability): failure associated with weight of train, inadequate soil strength, increased water content.

- Consolidation settlement: static soil stress increased caused by embankment weight, and saturated fine-grained soils.
- Frost action (heave and softening) : the track become rough caused by periodic freezing.
- Swelling/shrinkage: rough track surface caused by highly plastic soils, and changing moisture content.
- Slope erosion: Soil is eroded by running surface and subsurface water.
- Soil collapse: ground settlement caused by water inundation of loose soil deposits.

3. Fault chart development

The fault chart was developed in two stages. In first stage, cause-effect analysis is used to develop failure mechanisms depicted in the form of a diagram. In the second stage fault tree analysis (FTA) is utilized to facilitate the analysis of the faults [12].

These methods facilitate recognising the causes of drainage related railway track failure and provide a graphical representation of the interactions between the possible failure causes. Herein the charts were developed using engineering knowledge to determine the causes of the modes of drainage related track failure.

The application of this approach can help to:

- Identify influential factors which are associated with a particular type of railway subgrade failure.
- Assist the railway asset manager in selecting appropriate railway maintenance techniques through diagnosing the cause(s) of railway track failure, and subsequently the correct failure mode.
- Facilitate the development of risk based models to improve railway drainage asset management.

3.1. Cause-and-effect analysis

Cause-and-effect analysis is a technique for determining an undesirable event or problem based on its likely causes. The contributory factors are organized and structured by the broad categories considering all possible hypotheses [12].

3.2. Fault tree analysis (FTA)

FTA is a pictorial tree diagram technique (see Fig. 5) which relates a specified undesired event (called the "top event") with causal factors (intermediate and basic events). In order to perform the relationship, these are identified, organized, analyzed deductively in a logical manner[12].

4. Railway track subgrade failure mechanisms using cause and effect analysis.

A cause and effect analysis has been used to generate two subgrade failure charts (Fig. 6 and Fig. 7). One of these concerns track founded on fine-grained subgrades and the other railway track founded on an embankment. For the case of subgrade soils, the approach adopted has been to split the deterioration into two different general causes, namely the dynamic train induced loading regime and the natural environment (e.g. rainfall, flooding from rivers etc.) (i.e. the right hand part of the chart). These two factors are linked within the chart to lead to subgrade failure (the left hand side of the chart), see Fig. 6. The Embankment failure chart follows a similar approach, except that here embankment failure is only associated with environmental factors, see Fig. 7.

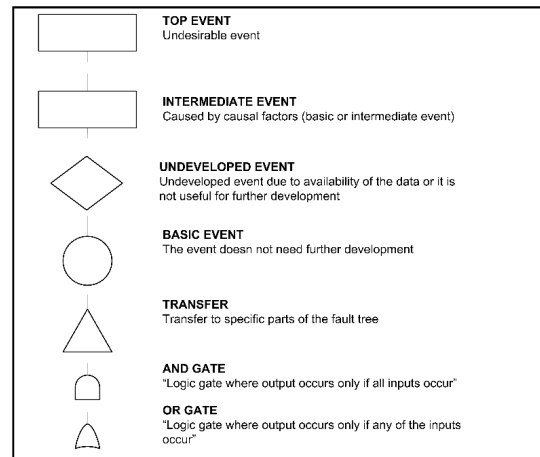


Fig. 5. Common relationship symbols in FTA (source : after[12,13]).

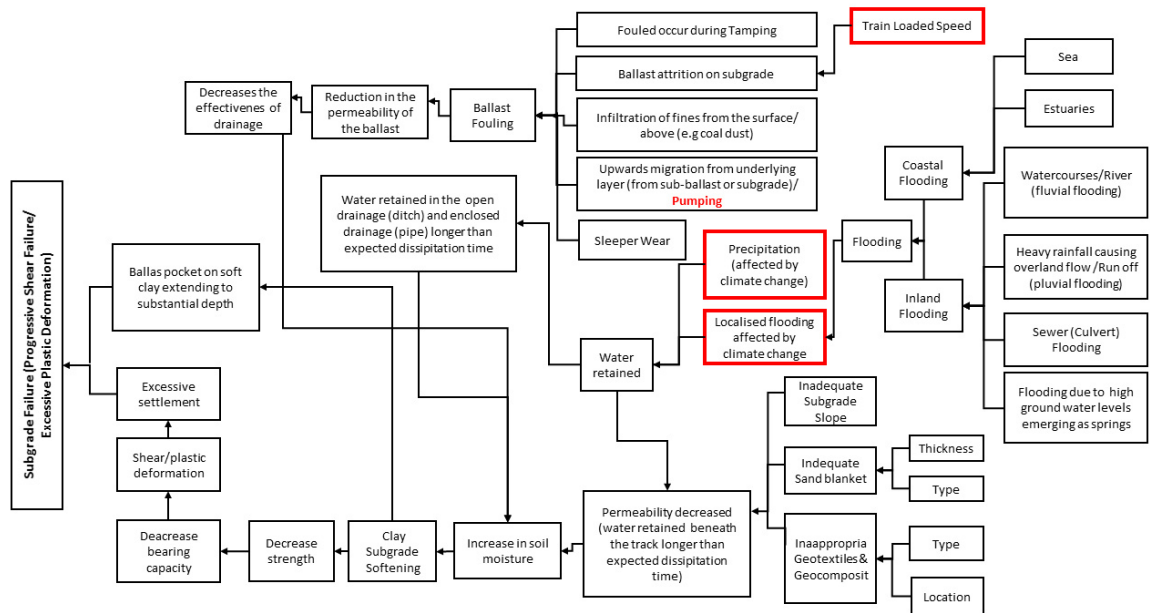


Fig. 6. Failure mechanisms using cause and effect analysis for railway track founded on fine-grained subgrades.

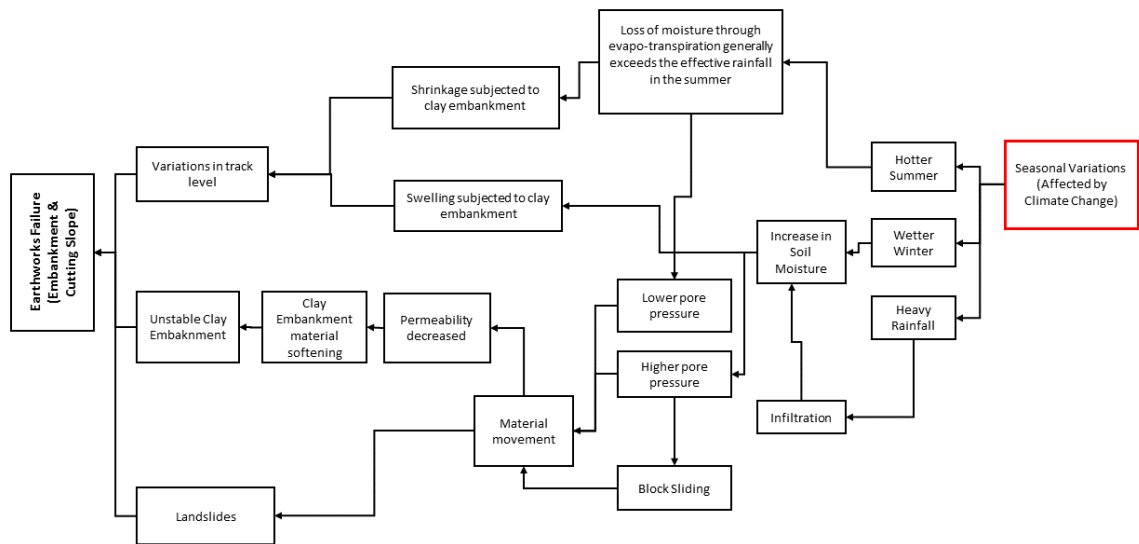


Fig. 7. Failure mechanisms using cause and effect analysis for railway earthworks (embankment/ cutting slope).

5. Using fault tree analysis (FTA) to perform the fault chart to identify the potential risk

The approach adopted using Fault Tree Analysis utilizing the information from the cause and effect analysis using a more structure approach. Here railway track failure associated with inadequate drainage is decomposed into three main failure types. Namely those associated with subgrade failure, drainage deterioration and embankment failure. Using the information from the previously generated cause and effect charts, the three main failure types are decomposed at a number of levels into their basic causes, see Fig. 8 and 9.

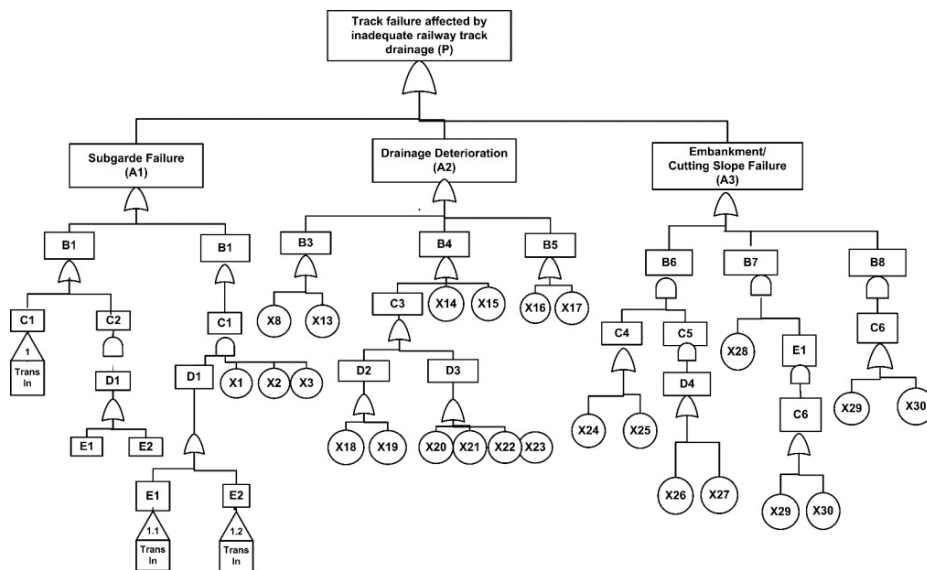


Fig. 8 Main FTA for track failure affected by inadequate railway track drainage.

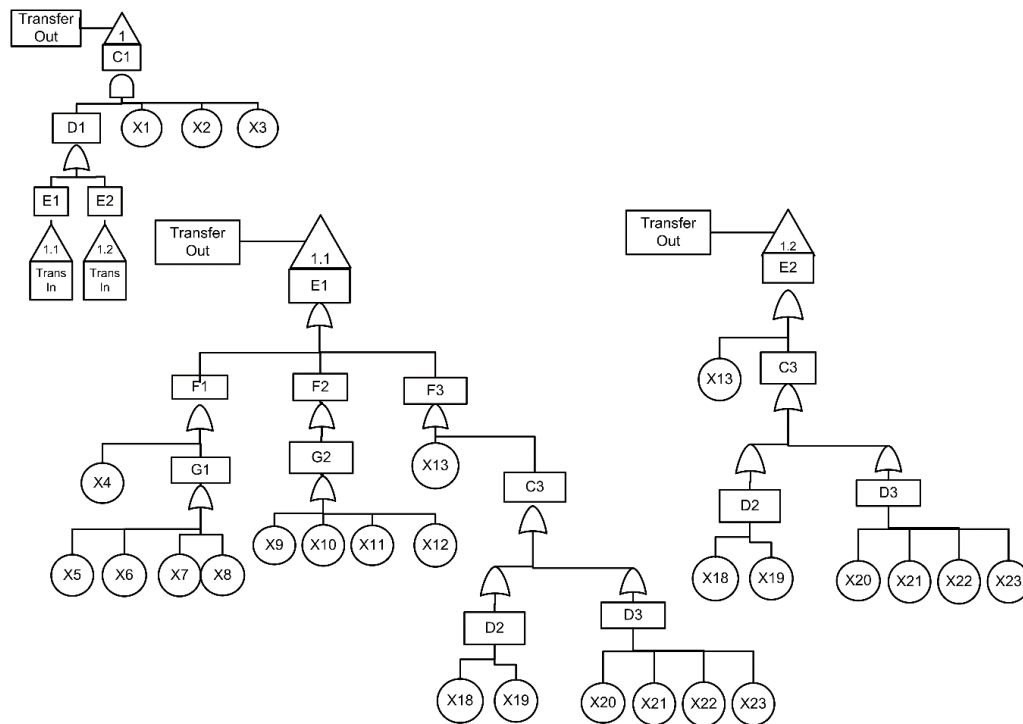


Fig. 9 Transfer-in FTA for track failure affected by inadequate railway track drainage.

Table 1 presents an alternative form of the fault charts, enabling the causes, or risks of railway track failure, associated with drainage issues, to be identified.

Table 1. Identified potential risk based on undesired event and its causal factors.

No	Event Code	Description	Associated with	No	Event Code	Description	Associated with
		BASIC EVENT				INTERMEDIATE EVENT	
1	X1	Decrease strength	C1	32	A1	Subgrade failure	B1,B2,P
2	X2	Decrease bearing capacity	C1	33	A2	Drainage deterioration	P
3	X3	Shear/plastic deformation	C1	34	A3	Embankment/cutting slope failure	P
4	X4	Lack of historical design data	F1	35	B1	Excessive plastic deformation(ballast pocket)	C1,C2,A1
5	X5	Inadequate subgrade slope	G1	36	B2	Progressive shear failure	C1,A1
6	X6	Inadequate sand blanket	G1	37	C1	Excessive settlement	X1,X2X3,D1B2
8	X8	Inadequate capacity of ditch/pipe	G1	39	D1	Subgrade softening	E1,E2,C1
9	X9	Fouled occur during tamping	G2	40	E1	Water retained beneath/below the track (permeability decreases)	F1,F2,F3,D1,C6,B7
10	X10	Ballast attrition	G2	41	E2	Water retained on the surrounding track	X13,C3, D1
11	X11	Pumping	G2	42	F1	Inappropriate design	X4,G1,F1
12	X12	Sleeper wear	G2	43	F2	Increase train load/speed	G2,E1
13	X13	Increase precipitation	B3, F3	44	F3	Climate change	X13,C3,E1
14	X14	Poor material	B4	45	G1	Inappropriate design for given environment	X5,X6,X7,X8,F1
15	X15	Poor supervision	B4	46	G2	Ballast fouling	X9,X10,X11,X12,F2
16	X16	Inadequate maintenance	B5	47	F3	Climate change	X13,C3,E1
17	X17	Lack of maintenance	B5	48	C3	Localised flooding	D2,D3,B3

No	Event Code	Description	Associated with	No	Event Code	Description	Associated with
		resource					
18	X18	Sea Flooding	D2	49	B3	Water retained in ditch and pipe	X8,X13,C3, A2
19	X19	Estuaries flooding	D2	50	B4	Poor construction quality	X14,X15,A2
20	X20	River flooding	D3	51	B5	Poor maintenance	X16,X17,A2
21	X21	Run off flooding	D3	52	D2	Coastal Flooding	X18,X19,C3
22	X22	Sewer flooding	D3	53	D3	Inland Flooding	X20,X21,X22,X23,C3
23	X23	Flooding due to high ground water levels	D3	54	B6	Variations in track level	C4,C5,A3
24	X24	Loss of moisture through evapotranspiration	C4	55	B7	Unstable embankment	X28,E1,B7
25	X25	Hotter summer	C4	56	C6	Material movement	X29,X30,E1,B8
26	X26	Heavy rainfall	D4	57	B8	Landslides	C6,A3
27	X27	Wetter winter	D4	TOP EVENT			
28	X28	Material softening	B7	58	P	Track failure affected by inadequate track drainage	A1,A2,A3
29	X29	Block sliding (higher pore pressure)	C6				
30	X30	Lower pore pressure affected by loss of moisture	C6				

6. Practical applications

The above has demonstrated an approach to developing a comprehensive understanding of the railway drainage associated failure which can be used to assist the diagnosis of the causes of failure. This information can be used directly in the specification of maintenance and remedial treatments by helping to identify the root cause of any problem, thereby enabling track maintenance to be targeted appropriately.

It can also be used to assist asset management approaches which enable the predictive risk based approaches to track maintenance to be developed.

By recognising symptomatic problems on the network, the railway asset manager can tailor and modify current practices, if necessary, to facilitate improved railway track maintenance and rehabilitation.

7. Conclusions

This paper has presented an approach to develop a thorough understanding of the causes of drainage related railway track failure. The approach combines the use of cause and effect analysis allied to fault tree analysis. The two stage approach developed fault trees firstly from a cause and effect analysis informed by the literature and expert opinion. The understanding of railway track drainage associated failure can be further used to infer engineering knowledge into railway performance models and associated risk analysis methodologies. The benefits of following such an approach include expected improvement on the predictive power and performance of purely mechanistic models.

For railway asset managers the Fault Trees can be used to: (i) Isolate the influencing failure factors, (ii) Identify the associated failure paths and the linkages between these and the influencing factors, and; (iii) Assist in diagnosing the cause of failure and thereby in specifying appropriate remedial measures.

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